

PROJECT-X, SRF, AND VERY LARGE POWER STATIONS*

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We seek to develop accelerator-driven subcritical (ADS) nuclear power stations operating at more than 5 to 10 GW in an inherently safe region below criticality, generating no greenhouse gases, producing minimal nuclear waste and no byproducts that are useful to rogue nations or terrorists, incinerating waste from conventional nuclear reactors, and efficiently using abundant thorium fuel that does not need enrichment. First, the feasibility of the accelerator technology must be demonstrated. Fermilab is developing concepts for Project X, which would use a superconducting RF (SRF) linear proton accelerator to provide beams for particle physics at the intensity and energy frontiers. We propose to extend this linac design to serve as a prototype for a practical accelerator that can drive several ADS reactors at once and also provide beams for reactor development.

1.1. Overview

A commercial GW-scale ADS power plant requires a proton accelerator with a beam power of at least 10 MW. Recent accelerator developments promise to make even more powerful accelerators feasible. There is a new opportunity to explore the relevant concepts in concert with another project, thereby achieving considerable synergies and cost savings. Namely, Fermilab is developing concepts for Project X, which would use a superconducting RF (SRF) linear accelerator that could deliver megawatts of beam power to provide beams for particle physics at the intensity and energy frontiers. One concept calls for an 8-GeV pulsed SRF linac; another concept is for a CW linac with a lower initial energy of about 2 GeV. One of the steps in proceeding through the Department of Energy's critical decision process from CD0 to CD1 is to look at alternative designs. In that spirit, Muons, Inc., Fermi National Accelerator Laboratory (Fermilab, High Energy Physics), Thomas Jefferson National Accelerator Facility (JLab, Nuclear Physics), and the Oak Ridge National Laboratory Spallation Neutron Source (SNS Basic Energy Sciences) have proposed to examine alternative designs for Project X that would be consistent with the needs of ADS and ATW. For example, the use of continuous-wave (CW) RF may

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enable production of tens of MW of beam power, considerably more than what is required for the intermediate-term HEP program at Fermilab, at a modest incremental cost relative to the baseline Project-X. The linac could serve as a prototype of a device that could drive several ADS reactors at one location, an approach which will become increasingly attractive with the development of the national power grid using low-loss transmission lines based on new superconductors.

The first major milestone of the project discussed here is to produce an enhanced or alternative design for Project X that includes ADS and ATW development needs. The planning, component development, construction, and operation of the machine will be the first step toward a practical accelerator for ADS and ATW based on SRF. Once constructed, the proton beam would allow tests and development of reactor components. Combining the goals of the High Energy, Nuclear Physics, and Basic Energy Sciences communities of DOE with the national energy and environment goals will lead to many desirable outcomes including lower costs, better technology, faster implementation, and the synergies that come from talented people working together to solve critical national and global problems.

Figure 1 shows the present and planned accelerator parameters that can be compared to the potential of a CW Project-X.

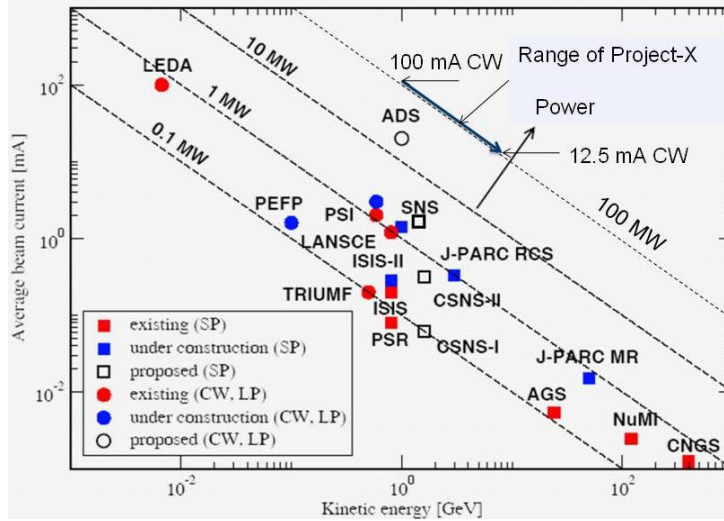


Figure 1: Present and planned high-intensity proton accelerators. Original data compiled by J. Wei and S. Henderson. The present power record is held by the ORNL SNS. The range of parameters that could be explored by Project-X is indicated on the 100 MW line.

In ADS schemes, spallation neutrons are produced by a 10 MW beam of protons on a high Z target. The fast neutrons (1-10 MeV) interact with Thorium 232 (fertile nucleus) to convert it to Protactinium which in turn decays into

Uranium 233 (Fissile nucleus). (Similarly for U 238, one can make Plutonium 239 which is fissile). Additional neutrons induce fission to produce power.

It has been shown that neutron production from a proton beam increases almost linearly with proton energy for energies above 1 GeV. Consequently, it is reasonable to consider beam power as the relevant variable such that a lower beam current accelerated to higher energy can provide the needed beam power. Or, as we propose here, a large current at higher energy can supply several ADS reactors in parallel.

Essential advantages of using a higher-power higher-energy machine to drive several ADS/ATW reactors simultaneously compared to one accelerator for each reactor include better efficiency and lower cost. By creating most of the beam power with higher-gradient, more-efficient SRF cavities operating where the proton velocity is close to the speed of light ($\beta=1$), capital and operating costs are reduced.

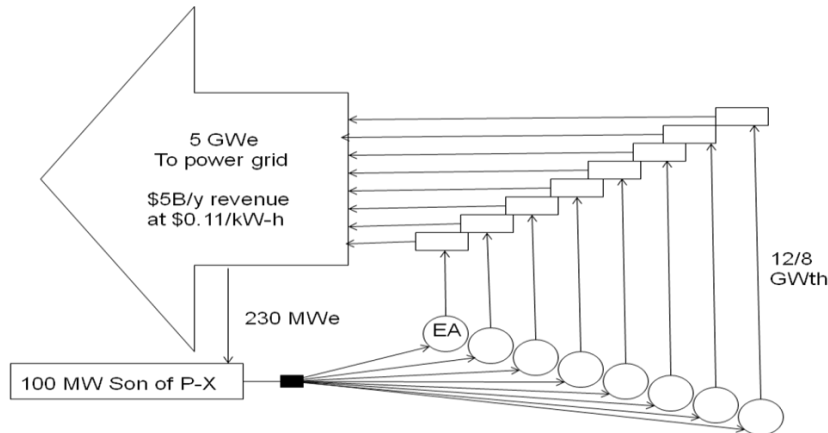


Figure 2: Schematic of a large power station that is driven by an SRF proton linac that could be developed using the proposed Fermilab Project-X. The 100 MW beam is distributed to 8 thorium-burning Energy Amplifiers (EA) as described by Carminati et al.[1]. Each EA feeds a steam turbine to provide power to the national grid.

1.2. Higher-Energy SRF Linacs

Since the 1993 study described above, SRF has become much more mature, with many examples of successful projects. The 6 GeV CW Continuous Electron Beam Accelerator Facility (CEBAF) at JLab has demonstrated reliable SRF operation, while advances in cavity construction and processing have shown higher gradients and quality factors that will lead to lower construction and operating costs for future machines. The 1 GeV SRF linac at the Spallation Neutron Source at ORNL, while operating in 60 Hz pulsed mode, is being used to explore many of the issues relevant to reliable operation and control of losses at high beam power that will be essential for ADS applications. A proton beam

power near the MW-level has already been achieved at SNS, thereby demonstrating the feasibility of one of the key technologies required for ADS. Free Electron Lasers and synchrotron light sources that are based on CW SRF are likewise becoming commonplace.

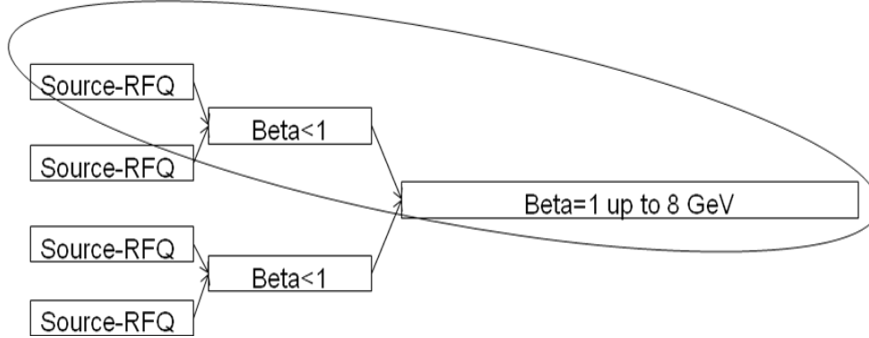


Figure 3: Schematic of an accelerator with sufficient redundancy to serve as a practical driver for the power station described in figure 2. The components enclosed by the ellipse represent Project-X.

The special additional requirement for ADS uses, and an important reason to have an ADS prototype, is that the accelerator must be extremely reliable. This requirement is motivated not so much by the desire for steady power output but by the concern that reactor components might be damaged by sudden changes in power level. We will propose to demonstrate this reliability by invoking a combination of component selection and redundancy, where figure 3 indicates how Project-X can be used for this development. For example, instead of fanning out power from one klystron to many RF cavities, we can use individual power sources for each cavity. A power source failure in this latter case can be compensated by adjusting the synchronous phase of the other cavities in the linac.

The original motivation for this proposal to operate Project X as a CW machine was to make sure that there would be sufficient beam power to satisfy future needs that might not yet be known. Considering that the present Booster synchrotron will have operated more than 40 years by the time it is replaced by Project-X, it seems also likely that there will be intensity needs that are yet to be imagined in the lifetime of Project-X. Developing beams for ADS reactors may be the first example of an otherwise unanticipated reason to have a generous supply of several-GeV protons at Fermilab. Potential high energy physics beneficiaries of such a proton source include a muon factory and a neutrino factory.

References

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